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Chapter 11

Conceptual and Practical Issues in Monitoring Disease in Wild Animal Populations: A Review of Avian Influenza Programs

Paul F. Doherty, Jr., Ph.D.[1]
Department of Fishery and Wildlife Biology,
Colorado State University, Fort Collins, CO 80523-1474

Robert G. McLean, Ph.D.
National Wildlife Research Center, WS/APHIS/USDA,
4101 LaPorte Avenue, Fort Collins, CO80521-2154

INTRODUCTION

Interest in monitoring has increased in recent years with the realization that monitoring data can be a key component to understanding and managing biological systems. Because of legislation such as the National Environmental Protection Act (1969), Endangered Species Act (ESA; 1973) and legislation focused on controlling diseases that can affect agricultural commerce, monitoring data is instrumental in management actions related to such legislation. However, even with the ubiquity and increased responsibilities of monitoring plans, some have viewed monitoring as "prostituting .... science to a trivial activity" (Krebs 1991), "displacement behavior" (Nichols 1999), "ecologically banal" (Krebs 1991), and as "datakleptomania" (Hellawell 1991). Many of these criticisms point to existing uncertainty concerning the role of monitoring, what to monitor, and what methods to employ, especially with limited resources. We will first provide a current review and appraisal of the underpinning philosophical approaches to monitoring plans.

The number of court actions related to the above legislation has also increased in recent years, bringing attention to the integrity of monitoring activities and related management actions. This spotlight will continue to focus more narrowly on the scientific rigor and design supporting such data collection. Management decisions will need to be based on data that are defensible in court (Federal Judicial Center 2000) and additional emphasis needs to be placed on examining the role of monitoring plans, as well as their designs, in management. No matter what philosophical approach is taken, attention to study design is needed. Animal monitoring programs continue to be plagued by the lack of use of prob-

*Corresponding Author email: paul.doherty@colostate.edu

ability-based sampling designs and the lack of attention to detection error. Secondly we will focus on these design issues and highlight some recent advances.

Finally we will review a series of contemporary, avian influenza monitoring activities in relation to underlying philosophical approaches and design features and provide recommendations.

PHILOSOPHICAL APPROACHES TO MONITORING

Monitoring programs are generally grounded in two frameworks, 1) an early-warning (Vos et al. 2000), retrospective (National Research Council 1995, Noon 2003,) surveillance (Nichols and Williams 2006), or serendipitous (Hellawell 1991) framework and, 2) an early-control (Vos et al. 2000), knowledge-gaining (Nichols 1999), or predictive (National Research Council 1995, Noon 2003,) framework. The first framework is also grounded in a human health analogy with the view that managers are "essentially family physicians" for a particular biological/ecological system (Davis 1993). Monitoring under this viewpoint is typified by the use of phrases such as 'monitoring the pulse of the planet' (Dougherty 2000) or monitoring 'vital signs' (National Park Service 2004) and can generally be described as part of a sequential program (Green 2002, Underhill and Gibbons 2002, Nichols and Williams 2006):

1) Monitor trends in a parameter of interest or index to that parameter (e.g., population abundance, prevalence of a disease).
2) If the trend is in a undesired direction, or the parameter estimate passes some 'trigger' or threshold of concern, then enter into a research program to determine the causes of the decline (or increase), including environmental factors.
3) Ameliorate and mitigate the causes such as environmental factor(s).

This framework is typified by the case of raptors and DDT (dichloro-diphenyl-trichloroethane, Underhill and Gibbons 2002). In the 1960's, ostensibly through monitoring, declines in birds of prey populations were noted. Through research the decline was found to be related to eggshell thinning and decreased reproductive success caused by metabolites of DDT (step 2 – identify the cause). DDT was taken off of the market and raptor populations are recovering (step 3 – amelioration). Similarly, many recent monitoring efforts for highly pathogenic H1N5 avian influenza virus have this philosophical underpinning. Samples are taken until the virus is detected (step 1). When the virus is detected, additional measures are employed to further understand the local spread of the disease (step 2) and eradication/control measures will be enacted (step 3).

Monitoring programs, under this framework, are predicated on being 'warning systems' by methodologically collecting time series of data on a number of parameters (often abundance or presence) and then searching for patterns within, and correlations among, these time series.

A number of criticisms have been levied against this early-warning framework (Hellawell 1991, Krebs 1991, Suter 1993, National Research Council 1995, Wicklum and Davies 1995, Nichols 1999, Nichols and Williams 2006). First, the human medicine analogy is untenable (Suter 1993, Wicklum and Davies 1995). Mammalian health is a property of individual organisms and implies consistent structure and development, tight integration, homeostasis, (Suter 1993) and the existence of an optimum condition (Wicklum and Davies 1995). Populations, communities, or ecosystems are not organisms, do not have clear boundaries (such as skin), do not have consistent structure and development, and lack the control systems to maintain homeostasis (Suter 1993). Nor are there fundamental, optimal states for organizational scales above the individual. Such optima would invoke group selection theory (Wicklum and Davies 1995).

The analogy between human health and ecological systems is worth further exploration. First, a medical doctor does not only examine one measure and declare a patient "60% healthy" (Suter 1993). Rather, a large number of measures are examined (e.g., body temperature, body weight, blood pressure, blood chemistry, etc.) and specific diagnoses are made. In contrast ecological monitoring programs are often based solely on a single measure (i.e., an indicator), and the 'health' state of the system is judged (Greenwood et al. 1995). Second, due to homeostasis, variation in human health measures is low. For example the coefficient of variation associated with body temperature is approximately 0.04% (Mackowiak et al. 1992) whereas the coefficient of variation associated with animal abundance is frequently much greater than 10% (Link and Nichols 1994). Sampling error is much less in human health measures than in ecological measures and large sampling errors in the later can compromise the ability to recognize meaningful patterns (Nichols 1999). Finally, experimentation in human health systems is under strict ethical and legal constraints. Because of these constraints, the gaining of knowledge is mostly limited to retrospective analyses and surrogate systems. Fortunately the gaining of knowledge is not as severely limited in this way for ecological systems; however ecological scientists often do not take advantage of this ability.

Beyond the poor analogy, the concept of 'health' is a value-laden abstraction, often leading to imprecise thinking and goals (Davis and Slobodkin 2004). This concept is often invoked as being solely scientifically based without recognizing the role of societal (i.e. ethical, economical, and political) value judgments (Wicklum and Davies 1995).

For the early-warning framework other criticisms, besides those focused on the human health analogy, have been leveled at the ability to gain knowledge efficiently (Nichols 1999). This argument states, at best, monitoring data collected under an early-warning framework can only provide weak-inferential, retrospective results, with the inherent value being in hypothesis generation. Stronger inferential science (Platt 1964, Romesburg 1981) and research are reserved for steps 2 and 3.

In the second framework, called an "early-control" (Vos et al. 2000), knowledge-gaining (Nichols 1999), or predictive (National Research Council 1995) framework, monitoring is typified by being a part of a program that is attempting to gain knowledge about a biological system constantly, not just after a problem is suspected (Nichols 1999). Testing a priori hypotheses, especially through manipulative experiments, will provide the strongest inferential knowledge (Platt 1964). This gaining of knowledge may be of a basic scientific nature and/or focused on possible management actions. This framework contends that a priori hypotheses concerning driving factors or possible management actions exist, and monitoring programs should be designed to test predictions resulting from these hypotheses. The monitoring data collected can still be used in a retrospective time trend, hypothesis-generating exercise, as in the early-control framework; however this is not the raison d'etre. Time trend analysis is the secondary product, rather than the main focus of monitoring. Under this framework useful knowledge is gained efficiently throughout the years of data collection. If understanding the basic ecological processes of a system is the focus of a monitoring program, then much more will be known about the system, especially if management actions are needed and must be developed. If management actions exist and are investigated throughout the time period, when a problem does occur, managers are more capable of addressing problems.

The catch-phrase 'adaptive management' (Walters and Holling 1990) also falls under this second framework. Unfortunately this term means many things to many people. We reserve the use of the term in the spirit of a dual-control process in which the dual objectives of gaining knowledge and reaching management objectives are sought through an optimal decision/control analysis (Kendall 2001, Williams et al. 2002). These methods are often rooted in operations research, which provides a quantitative basis for decision making. One example of the use of this concept is waterfowl harvest management in North America (Williams et al. 1996, Kendall 2001).

In the case of large-scale surveillance plans, often support for these programs are only available for short periods of time or for only a portion of the surveillance network or effort and the ability to test large-scale ecological hypotheses, or adapt the sampling over time, is limited.

DESIGN AND METHODOLOGICAL ISSUES

No matter what philosophical bent is taken, of paramount importance are proper parameter estimation and experimental and/or sampling designs (e.g., Yoccoz et al. 2001). If attention is appropriately paid to these aspects, studies and results will have integrity, and ultimately results will be defendable in court or convincing to program administrators and to oversight advisory or regulatory agencies at the local/state, national or international level. Calls for attention to proper design of monitoring programs have been made a number of times (e.g., Davis 1993, Thompson et al. 1998, Gibbs et al. 1999, Nichols 1999, Block et al. 2001, Yoccoz et al. 2001, Sauer 2003, Diffendorfer and Doherty 2004). Thompson et al. (1998) provide general guidelines for designing sample surveys and we will not dwell on those here. We do note the important initial steps of prioritizing and selecting objectives for any study should not be overlooked (Mace and Collar 2002, Noon 2003) and without a clear focus and objectives, a monitoring plan has a high likelihood of failure. We also note that the setting of priorities is based on available information, and because information is in a constant state of flux, priority-setting should be understood as a process, subject to modification and upgrading (Mace and Collar 2002). A monitoring program that evolves with gained information will fit more easily into a knowledge-gaining framework.

We will concentrate on two particular issues that have plagued large-scale wildlife survey designs – namely attention to recognizing the importance of probability-based sampling strategies and detection probabilities (Skalski and Robson 1992, Skalski 1994, Yoccoz et al. 2001, Pollock et al. 2002, Sauer 2003). Sauer (2003), following Skalski (1994), recognize these two issues as a 2-stage sampling design, where choosing sample units, using a formal probability-based sampling scheme, is the first stage and estimation of parameters of interest (e.g., density, prevalence) incorporating detection probabilities within units is the second stage.

PROBABILITY-BASED SAMPLING

In some instances resources are available to conduct a census, but if a sample will provide enough information, there is no need to spend additional resources conducting a census. More often, resources are not available to conduct a census (even if possible), and a sample must be relied upon to make inference to a larger population.

Sample surveys are commonly invoked in monitoring plans, especially large-scale plans. A sample survey is defined as observing a population without experimental manipulation. Sample surveys are usually distinguished from the related field of experimental design, in which deliberate manipulation occurs in order to observe the effect of the manipulation with proper randomization, control, and replication (Thompson 2002). A discussion of experimental designs is beyond the scope of this chapter but many references exist for the interested reader (e.g., Montgomery 2001). However, sampling may be an important aspect in experiments, especially large-scale experiments where not all areas can be sampled, or individuals observed. Sampling is also distinguished from observational studies in which little control exists over how observations are obtained (Thompson 2002). In sample surveys, a sample is deliberately selected to avoid factors making data unrepresentative, such as observations based on convenience, haphazard selection, judgment, or incidental sampling (Thompson 2002). Attention to sampling is important because the 'integrity of the sample' (Stuart 1984) is paramount for any larger inference to be made beyond than only to the sampled individuals, and this integrity starts with data collection. Otherwise the problematic GIGO (garbage in-garbage out) principle will be in effect, which unfortunately, can be misconstrued as 'garbage in-gospel out' (Scheaffer et al. 1996) by unsuspecting, or unknowing, users.

A sample should be collected under a probability-based scheme and proper estimators used if extrapolation is desired. Essentially every individual, or location, in a population must be potentially sampled. If this is not the case, then there will be no statistical inference to a larger population. To be sampled, a target population needs to be separated into a list of sampling units. This list is often referred to as a sampling frame (Thompson 2002). Sampling units from this frame need to be chosen in a probabilistic manner, such that all units have a chance of being included in the sample. Many disease sampling plans are predicated on first detection. In such cases more effort can be expended where a higher probability of occurrence is expected. However, some effort should be expended in all areas/populations of concern. Inevitably after a disease or disease organism is detected, estimated prevalence and spread over an area will be of interest. In addition, confirmation of the *a priori* prediction of the high probability areas, or situations, of detection will be assuring. In this case extrapolation will be of increased importance. Many standard sampling schemes exist to allow such extrapolation such as simple random sampling, stratified random sampling, cluster sampling, systematic sampling, adaptive sampling, doubling sampling and ratio estimators (Cochran 1977, Thompson 2002). More novel sampling plans that may have relevance to monitoring schemes, including disease surveillance, include dual frame (Haines and Pollock 1998) and spatially balanced (Stevens and Olsen 2004, Theobald et al. 2007) sampling plans. When designing a sampling plan, a trained statistician should be part of the design team. Next we will discuss issues relating to detection probabilities and associated methodology.

DETECTION PROBABILITIES

The challenge of dealing with detection probabilities, while not unique to wildlife studies, is most common in wildlife-related studies. Introductory college statistics classes generally do not cover this subject matter because in most other fields (e.g., business, engineering) detection probabilities are not a major concern. Thus many biologists are not exposed to this issue in introductory college classes and are ill-prepared to deal with it. The problem arises because wildlife are naturally selected to avoid predators, are generally mobile, and thus often not easy to detect. Few survey methods permit the detection of all individuals in an area. For example, when wildlife are counted, the raw count is not the true abundance, but some unknown proportion of the true abundance (i.e., some individuals are not detected, Lancia et al. 1994). This relationship can be expressed by $C = Np$ where C represents the count statistic, N represents the true abundance, and p represents the probability of detection. Only if $p = 1$ does the count statistic equal true abundance (the parameter ecologists are generally most interested in). Detection probabilities can vary over time and space and generate patterns falsely ascribed to a biological cause, as well as hide patterns of biological interest.

However, by rearranging the above equation such that $\hat{N} = C/\hat{p}$ an estimate of abundance can be obtained if an estimate of p is available. Many methodologies are available to estimate detection probabilities associated with count statistics (discussed below). If we rely on a count statistic without correcting for detection error, we are essentially using an index – an *ad-hoc* estimator of a parameter of interest. Too frequently indices with no theoretical underpinnings are relied upon (Anderson 2001, Yoccoz et al. 2001, Pollock et al. 2002, Sauer 2003) and uncertainty (partially due to detection error) in these estimators is ignored with no confidence intervals given. Often, the use of indices is justified with the claim that alternative methods are impractical, expensive, or have 'too many assumptions'. Notably, in general, an index will have stricter assumptions, although often unstated, than a direct estimator. With recent advances in estimating detection probabilities, and the inherent drawbacks of *ad-hoc* estimators, focusing on indices as default-monitoring metrics is unadvisable. When indices are used, assumptions should be carefully stated and, to the best of our ability, verified, and the index calibrated periodically.

Methodologies incorporating detection probabilities

General references for estimating demographic parameters, as well as detection probabilities are Borchers et al. (2002), Williams et al. (2002) and Royle and Dorazio (2008) These books describe many methods which, because of space constraints we will not cover here. We will highlight one class of occupancy models data (MacKenzie et al. 2006, Royle and Dorazio 2008) that we think will be useful in disease surveillance programs.

Much progress has been made in estimating occupancy, or prevalence rates, where data collected focus on presence/absence data. Occupancy probability is often calculated as the proportion of sites that are occupied; extinction probability as the proportion of occupied sites at time t not occupied at time $t + 1$; and colonization probability as the proportion of sites not occupied at time t occupied at time $t + 1$. However such presence-absence data, and resulting estimates, can be confounded by detection error (false negatives) and such data should more precisely be referred to as detection/non-detection data and not presence-absence data. Using such data with naïve estimators will most likely result in under-estimates of occupancy and over-estimates of extinction probabilities. Approaches incorporating detection into estimators of occupancy, extinction and colonization have been derived (MacKenzie et al. 2006, Royle and Dorazio 2008). These methods have been extended to deal with the situation of species co-occurrence (MacKenzie et al. 2004) where predictions of one species affected the occurrence of another (e.g., waterfowl and avian influenza), multiple scales (Nichols et al. 2008) such as where sampling may take place at a refuge level and at wetlands within a refuge, for multiple sampling states (Mackenzie et al. 2009) where, for instance, disease presence may be classified in different ways (e.g., infectious or recovered), as well as for state uncertainty (Kendall 2008). Kendall (2008) provides potential analysis approaches for many disease-related situations. Some occupancy methods are also starting to be applied in disease situations (e.g., Thompson 2007, Gómez-Díaz et al. 2010).

In this section we briefly described issues related to the design and analysis of survey data. This section is not meant to give a full understanding of these methodologies and issues, but to identify and briefly explain some recent advances. Experts in the field of experimental and survey design and estimation should be consulted in incorporating these methodologies and helping with optimal sample selection and allocation. Few monitoring programs account for both detection and spatial sources of error, but we think to do so is one hallmark of a good monitoring program. Many field researchers have complained about the lack of methodologies to estimate parameters of interest well. The statisticians have responded. The onus is now on the field researchers to incorporate these new methodologies into field protocols and return to the quantitatively minded with advice on what worked and did not work so additional progress can be made.

REVIEW OF SELECTED MONITORING PLANS

We present a review of selected avian influenza monitoring activities with respect to the underlying philosophy, sampling scheme, and incorporation of detection probabilities (Table 1). We also provide a brief description of the location of sampling, description of samples obtained, and a general goal of the activities.

All of the studies were grounded in an early-warning framework with a primary goal of detecting a trend in prevalence or a 'trigger' such as a first instance of HPAI. Some studies incorporated knowledge into their sampling plans to increase the probability of detecting such a trigger (e.g., by focusing on ducks or focusing in specific areas/habitats). Secondarily, many descriptive and correlative analyses were conducted. Rarely were such analyses evident in the planning of the data collection with an optimal allocation of effort considered. Although many studies provided insight into how sampling plans could be improved, rarely were individual sampling plans adjusted accordingly over time. By considering hypotheses that could be tested, and designing data collection accordingly, more reliable information may be able to be obtained beyond opportunistic post-hoc analyses. Although we have learned much from these studies, and some have resulted in first detections of AI, considering incorporating monitoring schemes into an early-control framework may be a more productive expenditure of effort.

The lack of attention to probability-based sampling and detection error was striking. Although many sampling plans were undertaken on a large spatial scale, results could not be statistically extrapolated because of the lack of probability-based sampling designs. The

Table 1. Summary of selected avian influenza sampling programs

Location	Samples obtained	Goal	Philosophical underpinning	Probability based sampling	Detection probability	Citation
Canada	Cloacal swabs collected from duck banding operations	Provide baseline information of AI strains in ducks and early HPAI detection	Early-warning	No	No	(Parmley et al. 2008)
Two wildlife refuges in Italy	Serum and cloacal swab samples	Provide information on AI strains in wild ducks in Italy	Early-warning	No	No	(De Marco et al. 2003)
Northeast Germany	Environmental avian feces and urine from coastal aquatic birds	Provide information on AI strains and early HPAI detection from environmental samples	Early-warning	No	No	(Pannwitz et al. 2009)
Mostly Netherlands and Sweden, but also from sites worldwide	Cloacal swabs from 323 species	Provide information on AI from wild birds	Early-warning	No	No	(Munster et al. 2007)
Lake Constance, Germany, Switzerland, Austria	Cloacal and/or oropharyngeal swabs from dead wild birds (mostly waterfowl)	Provide information on H5 AI from dead wild birds	Early-warning	No	No	(Happold et al. 2008)
Alberta, Canada; Delaware Bay, NJ	Cloacal swabs and fecal samples	Provide information on AI from wild ducks, shorebirds, and gulls	Early-warning	No	No	(Krauss et al. 2007)
Germany	Tracheal swabs, Cloacal swabs, serum, and fecal samples	Provide information on AI in storks	Early-warning	No	No	(Muller et al. 2009)
Pacific Flyway, USA	Cloacal swabs	Provide information on AI from live and dead wild waterfowl and shorebirds	Early-warning	No	No	(Dusek et al. 2009)
Northeast Japan	Fecal samples	Provide information on AI from northern pintails	Early-warning	No	No	(Jahangir et al. 2008)
Argentina	Cloacal swabs	Provide information on AI from wild birds	Early-warning	No	No	(Pereda et al. 2008)
						(Pearce et al. 2009)
Alaska	Cloacal swabs and fecal samples	Provide information on HPAI H5N1 (and other AI) from wild birds	Early-warning	No	No	(Ip et al. 2008)
Alaska	Cloacal swabs and fecal samples	Provide information on HPAI H5N1 (and other AI) from wild birds	Early-warning	No	No	(Winker et al. 2007)

lack of attention to detection issues suggests that all of the results are minimum estimates since false negatives are likely to be present in the data set. Patterns in detection may also obfuscate correlative analyses that have been conducted.

Such patterns in underlying philosophies and attention to sampling concerns in AI monitoring schemes are also common in many large-scale wildlife monitoring schemes such as the Christmas Bird Count (CBC, National Audubon Society 2003), North American Breeding Bird Survey (BBS, USGS 2001b), Monitoring Avian Productivity and Survivorship program (MAPS, Desante et al. 1995, DeSante et al. 1999), North American Amphibian Monitoring Program (NAAMP, USGS 2001a), National Park Service Vital Signs (http://science.nature.nps.gov/im/monitor/index.htm, National Park Service 2004), and the US Forest Service National Protocol for Monitoring Vertebrates (Manley et al. 2004). These monitoring plans are based on an early-warning framework with the focus on detecting trends in organisms or indices of interest. Only the North American Waterfowl Management Plan (Nichols et al. 1995) is specifically based upon an early-control ('adaptive management') framework. The only plan incorporating detection probabilities into estimation, using a probabilistic sampling plan, and relying upon an early-control framework is also the North American Waterfowl Management Plan. This plan is also arguably the best large-scale monitoring plan (Nichols et al. 1995), with all other plans having been subjected to, sometimes severe, criticism (e.g., Sauer 2003). These criticisms are focused on underlying philosophies, such as the National Research Council (1995) suggesting plans such as these should not be based on a retrospective philosophy.

We believe monitoring plans more closely aligned with an early-control philosophy, with clear objectives, robust study plans (i.e., attention to error associated with detection and sampling in space), and with good execution will further our knowledge base and lead to better management, as well as be defensible. We believe that inferences in ecological disease research and epidemiology could be improved by considering these components.

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